Defense Technical Information Center Compilation Part Notice

ADP023789

TITLE: Powering and Motion Predictions of High Speed Sea Lift [HSSL] Ships

DISTRIBUTION: Approved for public release, distribution unlimited

This paper is part of the following report:

TITLE: Proceedings of the HPCMP Users Group Conference 2007. High Performance Computing Modernization Program: A Bridge to Future Defense held 18-21 June 2007 in Pittsburgh, Pennsylvania

To order the complete compilation report, use: ADA488707

The component part is provided here to allow users access to individually authored sections of proceedings, annals, symposia, etc. However, the component should be considered within the context of the overall compilation report and not as a stand-alone technical report.

The following component part numbers comprise the compilation report:
ADP023728 thru ADP023803

Powering and Motion Predictions of High Speed Sea Lift (HSSL) Ships

Joseph Gorski and Ronald Miller
US Naval Surface Warfare Center, Carderock Division (NSWCCD), West Bethesda, MD
{joseph.j.gorski, ronald.w.miller}@navy.mil

Pablo Carrica, Mani Kandasamy, and Fred Stern
The University of Iowa, IIHR – Hydroscience & Engineering, Iowa City, IA
{pcarrica, mkandasa}engineering.uiowa.edu and frederick-stern@uiowa.edu

Abstract

High Speed Sea Lift (HSSL) is an important area of interest for the US Navy. Computational tools are needed to predict the hydrodynamics of these configurations for their proper design and analysis in many areas including: resistance and powering, motions and habitability, loads in service and maneuverability. In particular, computational approaches requiring a minimum of empiricism are desired as there is a limited experimental database available for these ship concepts. To achieve this, efforts are underway to apply high-end unsteady Reynolds-Averaged Navier-Stokes (URANS) computations to these configurations in nearly all aspects relevant to their hydrodynamics analysis and design. The present effort concentrates on ship operations and the use of controllers for maneuvering and powering. Results are demonstrated for a 30 degree change of heading for a destroyer as well as a waterjet equipped HSSL concept accelerating from rest to the self propulsion point for a given speed. These predictions are computationally intensive and thus require high performance computing resources, but they are paving the way for a computational capability to aid in the design and analysis for a new generation of naval ships.

1. Introduction

This effort is in response to the current US Navy interest in HSSL ships that will allow rapid deployment of forces from CONUS to foreign ports and the need for computational tools to predict the hydrodynamics of these concepts. The computational hydrodynamic tools need to be able to predict the resistance of multihull vessels up to at least sea state 4, propulsive performance, seakeeping and structural loads on these vessels through survival sea states, maneuvering characteristics of the vessels, and the effects of shallow water on the performance of the vessels. Computational capability is needed for early stage design analysis through to detailed evaluation of final configurations. Consequently, a suite of computational tools is being developed and evaluated for predicting the performance of these vessels from simple inviscid methods to high end viscous techniques, which require High Performance computing Modernization Program (HPCMP) resources.

To predict viscous flow physics correctly the unsteady URANS code CFDShip is being used. Basic computational capability for various hull forms of relevance, including monhulls and multihulls, has previously been demonstrated (Stern, et al., 2006). This paper addresses current efforts to more realistically predict ship hydrodynamic behavior under actual operating conditions, which includes ship control. To predict the real behavior of ships it is necessary to not only predict the responses, as demonstrated previously, but the actual ship behavior in waves and while maneuvering. This involves the ability to do prescribed maneuvers such as overshoots, undershoots and steady turns to characterize the ship behavior as well as course keeping in waves. This makes it necessary to account for moving appendages and model the propulsor. Powering predictions are an important aspect of this effort which requires properly accounting for propeller and rudder interactions for conventional propeller arrangements. Initial demonstrations are being performed on conventional monohulls for eventual comparison with existing experimental data. In addition, waterjets are currently viewed as the propulsor of choice for certain speed ranges and some high speed concepts include both conventional open and waterjet propulsion systems. Waterjets have significant interactions with the hull boundary layer and computations must directly include the hull and waterjet to properly simulate these interactions. Consequently, viscous effects are important to both the waterjet prediction, since the incoming boundary layer is ingested into the propulsor, and to the maneuvering and seakeeping behavior as viscous vortices

0-7695-3088-5/07 $25.00

shed off of the hull influence the ship behavior as well as the interaction of upstream hull boundary layers with the rudders, which will be partially embedded in the hull boundary layer. To move toward a non-empirical capability for predicting such flow physics high fidelity codes such as CFDShip are needed. This paper discusses progress in bringing these components together to provide a complete capability for predicting HSSL surface ship behavior.

3. CFDShip

CFDShip is a general-purpose research URANS code developed at the University of Iowa over the past decade for support of student thesis and project research as well as transition to Navy laboratories, industry, and other universities. Basic solver numerical modeling details include 2nd-order upwind convective terms and 2nd-order central differenced viscous terms. The velocity and pressure are coupled using a Pressure Implicit Split Operator (PISO) algorithm. For the time derivatives a 2nd-order backward difference is used. Advanced iterative solvers available in the Portable, Extensible Toolkit for Scientific Computation (PETSC) are used to solve the Poisson (elliptic) pressure equation. Turbulence modeling uses Menter's blended k-ω/k-ε model (Menter, 1994). The solver uses MPI-based domain decomposition for parallel processing. Ghost cells are used to retain high order stencils across split block boundaries. The addition of multiple-body specification allows bodies to move independently of one another and individual body surface force integrations for force analysis can be obtained. The current version of the code, CFDship version 4 (Carrica, et al., 2006 & 2007) can model high-speed free surface flows using single-phase level-set to detect the free surface; overset grids for complex geometries and local refinement; detached-eddy-simulation (DES) turbulence models; and six-degrees-of-freedom (6DOF) motions. For ship motions, arbitrary heading, regular and irregular, unidirectional and multidirectional waves were implemented.

To allow for the computation of large-amplitude motions a dynamic overset grid technology was used. This is accomplished using the interpolation tool SUGGAR (Noack, 2005). The dynamic overset capability also allows for the handling of multiple independent and dependent objects, such as active control surfaces and rudders, which are needed to simulate ship operations. SUGGAR is used to blank (turn-off) points inside closed solid boundaries and to establish communication between overlapping grids via fringe points and donor cells. SUGGAR is run as a preprocessor for static calculations or concurrently with CFDShip for simulations using dynamic grid motions. Communication and synchronization between CFDShip and SUGGAR uses a UNIX first-in/first-out (FIFO) communication pipe. The software, named Unique Surfaces Using Ranked Polygons (USURP), developed by Boger (2006), is used to properly compute area and forces on overlapping surface regions.

Significant progress in predicting the hydrodynamics of HSSL ships has already been demonstrated with CFDShip (e.g., Stern, et al., 2006, Miller, et al., 2006). This included calculations in many areas directly relevant to the design needs for these concepts. Demonstrations include: resistance predictions over the entire range of speeds of interest for a number of multihulls and monohulls, which were validated with experiments; water-jet self propulsion was demonstrated using CFDShip at a design Froude number using thrust based on the resistance values obtained from the bare hull simulations; seakeeping calculations were demonstrated for a number of wave-lengths and wave amplitudes of interest, which showed non-linear behavior of the motions and added resistance for the higher amplitude cases. CFDShip was also used for preliminary keel slamming load predictions for a trimaran in regular waves.

3.1. Controller

Active and passive controllers have been implemented in CFDShip. Controllers offer a flexible way to impose simple maneuvers, replicate experimental conditions, and analyze ship performance under different situations. CFDShip currently has controllers to impose a variety of acceleration ramps in ship forward speed and propeller rotational speed, turning and zig-zag maneuvers, Proportional-Integral-Derivative (PID) speed control (controlling a propeller body force model or a fully modeled rotating propeller), PID heading control (controlling rudder angle), PID autopilot (using simultaneously speed and heading control) and waypoint control (using autopilot with variable heading). Controllers add to CFDShip the capability of analyzing several new types of problems. These include:

1. Classic maneuvering tests: the ship is accelerated to the desired approach speed using a speed controller, and then the controlled maneuver begins.
    a. Turning tests: a combined turning cycle requires operating the rudder at maximum rudder rate to a prescribed angle, and, once steady-state has been reached and the turning radius and tactical diameter determined, put the rudder back to zero at maximum rudder rate.
    b. Zig-zag test: the rudder is operated at maximum rudder rate to a prescribed angle. When the ship heading reaches the desired

heading check angle the rudder is steered at maximum rudder rate to the same angle in the opposite direction. The process is repeated on each side, resulting in a zig-zag trajectory.

2. Self-propulsion tests
   a. Speed-controlled tests: a speed controller is used to determine the self-propulsion point for a given Froude number. Revolutions per minute (RPM), resistance, sinkage, and trim are predicted.
   b. Ramp-controlled (full curve): the rotational speed of the propeller is incremented slowly to cover all speeds of interest in a quasi steady-state way. For each RPM, the velocity, resistance, sinkage, and trim are predicted.
3. Seakeeping
   a. Course-keeping in waves: an autopilot is activated when a ship is advancing in waves. The rudder action and the ability to keep the desired course are studied.
   b. Capsize/broaching: effect of control and steering strategies on dynamic stability can be studied. The role of autopilots in capsize, broaching, or other extreme events can be analyzed.

The controllers are either logical based on on/off signals and limiting action parameters, or active PID type. Limiters of action use physical limits of the actuators to add reality to the resulting actuator setting. For instance a rudder has a maximum and minimum operational angle, and a maximum allowed rudder rate. PID controllers use the classical action law:

$$\frac{d\phi}{dt} = Pe + I\int_0 edt + D\frac{de}{dt} \tag{1}$$

where ϕ is an action parameter, for instance the rudder angle, and e is the error of the controlled value with respect to the target value (for instance heading respect to desired heading), given by

$$e = \psi - \psi_{\text{target}} \tag{2}$$

The PID cruise controller uses a feedback loop, which in this example corrects for the error between the present heading and a target heading by making adjustments to the rudder angle at each time step. The adjustments are composed of three components: 1) a term proportional to the error in heading, 2) a term proportional to the integral of the error, and 3) a term proportional to the time derivative of the error. The PID controller parameters are currently held constant throughout the computation.

4. Results

Shown here are demonstrations with the URANS solver CFDShip for a conventional and HSSL concept hull. Previous computations demonstrated capability in the areas of resistance, maneuvering, and seakeeping. The present effort concentrates on ship operations and the use of controllers for maneuvering and powering of the ship. Results are demonstrated for a 30 degree change of heading for a destroyer as well as a waterjet equipped HSSL concept accelerating from rest to the self propulsion point for a given speed. Significant efforts are still underway and must continue to be pursued to demonstrate the accuracy of the computations in all of these areas as well as what can be done to efficiently achieve good accuracy.

4.1. Heading Change

This example demonstrates the use of both the speed and heading PID controllers for a destroyer configuration. The destroyer, represented as Model 5512, is appended with rudders for this simulation as shown in Figures 1 and 2. In this example, a target ship speed and target heading of $\theta = 30°$ degrees east of north is prescribed. The autopilot uses a PID speed controller, as shown in Eq. (1), with nondimensional constants P = 100, D = 100 and a heading controller with constants P = 2 and D = 10. The controllers are used to modify the propeller rpm and the rudder angle deflection, subject to minimum and maximum values and maximum rates of change. A Hough and Ordway body force model is used to simulate the twin propellers. The advance coefficient for the propellers is computed based on the current ship velocity, and open water curves are used to calculate the thrust force input on the equations of motion for the ship. Six degrees-of-freedom are used to compute the motions of the ship.

The calculation is performed at model scale in calm seas. The calculation begins with the ship at rest and pointing north, $\theta = 0°$. Initially both the speed and heading are much different than their respective target values, so that the propeller revolutions per second (RPS) and rudder deflections increase rapidly. As the speed approaches the target value, the RPS changes much more slowly. As seen Figure 3, the speed approaches the target value quickly without much overshoot. The ship heading also approaches its target quickly, but oscillates about the target as the rudder angle changes sign to compensate for the overshooting and undershooting. Figure 4 shows the resulting trajectory.

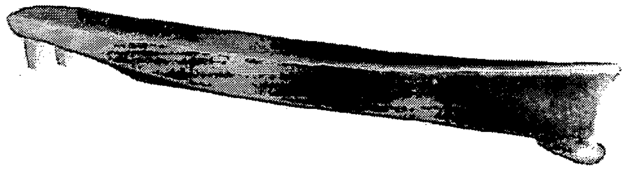


Figure 1. Model 5512 appended with rudders

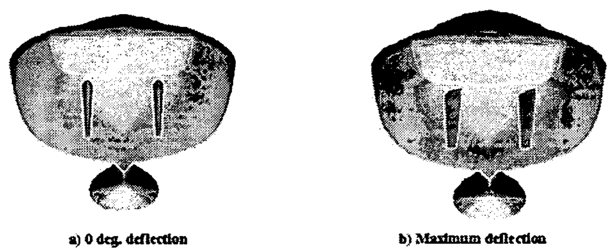


Figure 2. Rudder at two different angles

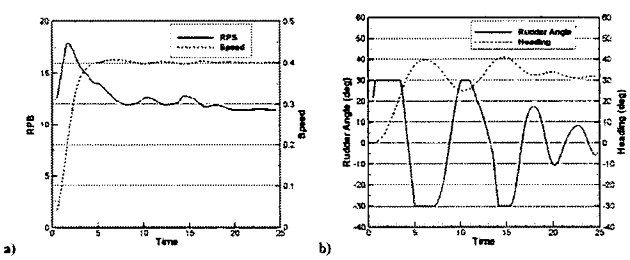


Figure 3. Speed and rudder control: a) RPS and speed vs. time; b) Rudder angle and heading vs. time

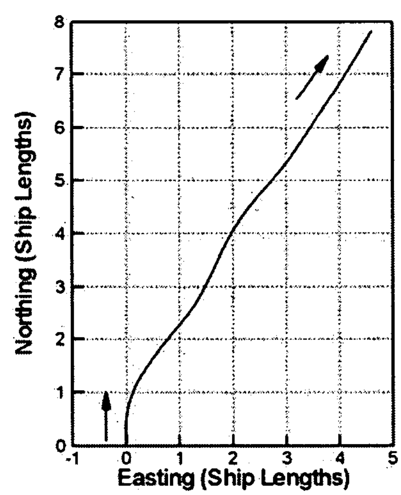


Figure 4. Ship Trajectory

4.2. Waterjet Self Propulsion

As mentioned waterjet propulsion systems need to be considered for HSSL concepts. To demonstrate this capability with CFDShip simulations are being performed for various configurations with waterjets. Shown here are computations of the centerhull of Model 5594, a high speed sealift trimaran concept, corresponding to experiments performed by Wilson, et al., (2004). The hull is slender with L/B = 16.65 and has a wide, rounded-bilge rectangular-shaped transom. The full scale design speed is 55 knots corresponding to a Froude number of 0.511 and a model scale Reynolds number of about 29 million, based on model length. The model is fitted with four waterjets arranged across the transom as shown in Figure 5. The waterjet inlets are flush with the hull just forward of the transom. The waterjet exits are fitted with converging nozzles with centerlines at the static waterline when at rest. The propulsor in each waterjet is simulated using a simple actuator disk to generate thrust. The body force applied in the actuator disk model is derived from open water curves of a propeller at a given value of rpm. To achieve self-propulsion of the model for Froude number 0.511, the PID cruise controller is used to determine the rpm. Initially the ship is at rest and the waterjets are not submerged as seen in Figure 6. To start the model an initial RPS of 10 is set for the actuator disk model. As time advances the controller adjusts the propeller RPS until the ship speed converges to the target Froude number of 0.511. Similar to the destroyer the RPS value increases rapidly initially, when the ship speed is much different than the target speed, but when the speed is close to the target speed the controller adjustments to the RPS are small. When the target speed is obtained, the thrust generated by the actuator disks matches the opposing friction and pressure forces resulting in zero net acceleration. At this point self-propulsion is achieved. Now the waterjets are fully operating and water exits from them interacting with the free surface. Also shown is Figure 6 is how the transom below the exit nozzles has cleared at this speed. Shown in Figure 7 is the free surface behind the transom with and without the waterjets operating. The waterjets interact significantly with the free surface immediately behind the transom. Surface pressures and streamlines on the underside of the hull are shown in Figure 8 with and without the operating waterjets. Again significant differences are seen in the streamline behavior, due to flow entering the waterjets, and the pressure field created around the inlets, which can impact resistance. It is also seen in Figures 7 and 8 that there are differences in the flow entering and exiting the inboard and outboard waterjets. All this needs to be computed directly to properly simulate the inlet and hull interactions critical to predicting waterjet performance accurately.

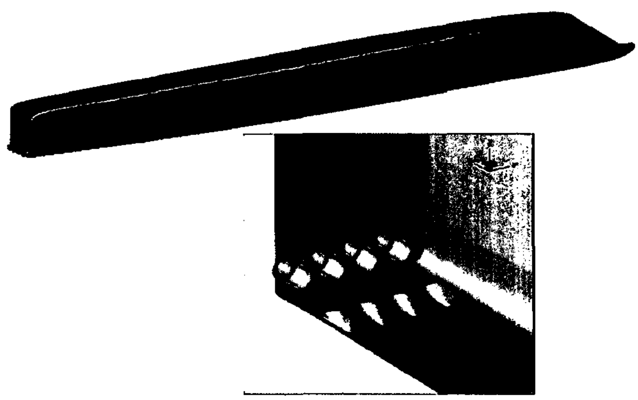


Figure 5. Model 5594 centerhull and waterjets

5. Summary

Predicting the hydrodynamics of high speed sea lift ship configurations provide many of the same challenges associated with traditional monohulls as well as additional challenges related to hull interactions, waterjets and other design considerations where experience is limited. Consequently, computational tools are needed to predict the hydrodynamics of these configurations. In particular, computational approaches requiring a minimum of empiricism are desired as there is a limited experimental database available. Such a computational approach is clearly needed for the design and analysis of future US Navy ships having HSSL capability. To achieve this, efforts are underway to apply high-end URANS computations to these configurations in nearly all aspects relevant to their hydrodynamics analysis and design. Shown here are demonstrations with the URANS solver CFDShip concentrating on ship operations and the use of controllers for maneuvering and powering of a ship. Results are demonstrated for a 30 degree change of heading for a destroyer as well as a waterjet equipped HSSL concept accelerating from rest to the self propulsion point for a given speed. Significant efforts are still underway and must continue to be pursued to demonstrate the accuracy of the computations in these areas as well as what can be done to efficiently achieve such accuracy.

Acknowledgements

The authors are grateful to the US Department of Defense's High Performance Computing Modernization Program that provided the computer resources at the Naval Oceanographic Office on the IBM P4 and at the Aeronautical Systems Center on the SGI 03K and the SGI Altix Bx2 as part of this Challenge Project. The research is supported by the Office of Naval Research under the administration of Dr. L. Patrick Purtell. The Naval Surface Warfare Center, Carderock Division's effort is also partially supported by In-House Laboratory Independent Research funds under the administration of Dr. John Barkyoumb.

References

Boger, A.D., "User's Manual for USURP, Unique Surfaces using Ranked Polygons." Penn State University, Applied Research Laboratory Manual, 2006.

Carrica, P.M., R. Wilson, R. Noack, T. Xing, M. Kandasamy, J. Shao, N. Sakamoto, and F. Stern, "A Dynamic Overset, Single-Phase Level Set Approach for Viscous Ship Flows and Large Amplitude Motions and Maneuvering." *Proceedings 26th ONR Symposium on Naval Hydrodynamics,* Rome, Italy, 2006.

Carrica, P.M., R.Wilson, and F. Stern, "An Unsteady Single-Phase Level Set Method for Viscous Free Surface Flows." *Int. J. Num. Meth. Fluids*, Vol. 53, pp. 229–256, 2007.

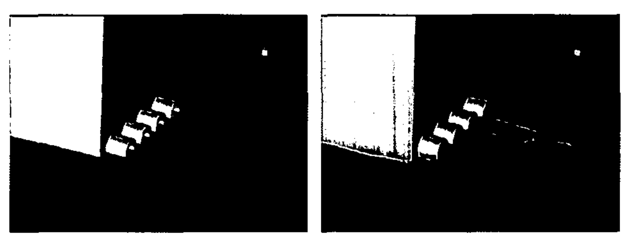
Menter, F.R., "Two-Equation Eddy Viscosity Turbulence Models for Engineering Applications." *AIAA J.*, Vol. 32, pp. 1598–1605, 1994.

Miller, R., P. Carrica, M. Kandasamy, T. Xing, J. Gorski, and F. Stern, "Resistance Predictions of High Speed Mono and Multihull Ships with and without Water Jet Propulsors using URANS." *Proceedings 26th Symposium on Naval Hydrodynamics*, Rome, Italy, Sept. 2006.

Noack, R., "SUGGAR: a General Capability for Moving Body Overset Grid Assembly." 17th AIAA Computational Fluid Dynamics Conf., Toronto, Ontario, Canada, 2005.

Stern, F., P. Carrica, and M. Kandasamy, et al., "Computational Hydrodynamic Tools for High-Speed Sealift." Presented at the SNAME Maritime Marine Technology Conference, Fort Lauderdale, FL, October 2006.

Wilson, M.B., C. Chesnakas, S. Gowing, et al., "Analysis of Hull Boundary Layer Velocity Distributions With and Without Active Waterjet Inlets." Waterjet Propulsion IV, London, England, May 2004.



(a) Initial undisturbed free surface (b) Free surface with operating waterjets

Figure 6. Model 5594 centerhull and waterjets

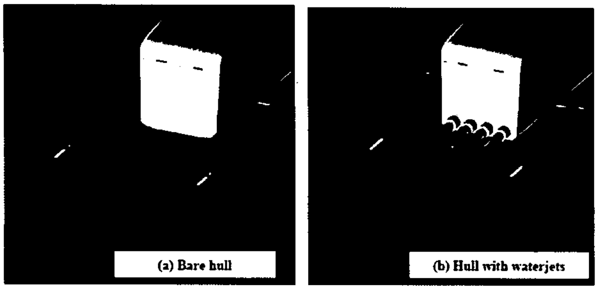


Figure 7. Free surface at stern with and without operating waterjets

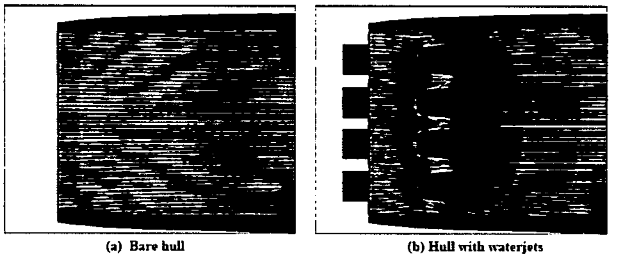


Figure 8. Surface pressures and streamlines with and without operating waterjets